

MARE BASALT PETROGENESIS REVISITED: Rb/Sr, Sm/Nd and Lu/Hf FRACTIONATION FACTORS, MANTLE SOURCE REGIONS AND CRUSTAL CONTAMINATION. I. Stewart McCallum and Emily K. Mullen, Department of Earth and Space Sciences, University of Washington, Box 351310, Seattle, WA 98195-1310 (mccallum@u.washington.edu).

Introduction: Many questions regarding the petrogenesis of mare basalts remain unresolved. Trace element and isotope geochemists tend to view the range of mare basalt compositional groups as independent primary magmas and develop mantle melting models to explain the compositional diversity [e.g. 1, 2, 3]. On the other hand, petrologists view the mare basalt suites as non-primary and suggest that no primary magmas have been sampled by the Apollo missions or lunar meteorites [4]. Since isotopic ratios (Sr, Nd, Hf, Pb) are not fractionated by magmatic processes, these elements can be used to “see” at least part way through the haze imposed by post-melting processes. Isotopic compositions of mare basalts can be used to address aspects of mare basalt petrogenesis. Recent data on early lunar chronology obtained in part from increased precision in ages of events in the first 100 million years of solar system evolution, coupled with new data on Hf-W systematics, permit a more precise calculation of the compositional and isotopic evolution of the Moon and its mantle reservoir.

We have calculated the fractionation factors (Rb/Sr, Sm/Nd and Lu/Hf) for mare basalts using the following equation: (equivalent equations are used to calculate $f_{\text{Sm/Nd}}$ and $f_{\text{Lu/Hf}}$):

$$f_{\text{Rb/Sr}} = \frac{\left(\frac{87\text{Rb}}{86\text{Sr}}\right)_0^B \left[e^{\lambda T_s} - e^{\lambda T_x} \right]}{\left(\frac{87\text{Sr}}{86\text{Sr}}\right)_{T_x}^B - \left(\frac{87\text{Sr}}{86\text{Sr}}\right)_{T_l}^M - \left(\frac{87\text{Rb}}{86\text{Sr}}\right)_{T_l}^M \left[1 - e^{-\lambda(T_l - T_x)} \right]}$$

where $f_{\text{Rb/Sr}}$ is the fractionation of basalt magma relative to its mantle source at the time of crystallization (T_x). T_0 , T_s , and T_l refer to the present day, the time of mantle source formation and time of lunar accretion, respectively. Superscripts B and M refer to the basalt and whole Moon, respectively. Formation of the lunar mantle is assumed to have been complete by ~60 Ma after solar system formation [5]. $^{87}\text{Rb}/^{86}\text{Sr}$ in the lunar mantle is set at 0.015. Calculated fractionation factors are not particularly sensitive to changes in either of these numbers. Fractionation factors for Rb/Sr and Sm/Nd are shown in Figs. 1 and 2. High-K Apollo 11 basalts are clearly distinct from **all** other mare basalts in terms of their Rb/Sr fractionation and are high-

lighted in red in Figs. 1 and 2 (average $f_{\text{Rb/Sr}} \sim 4$). 55% of the $f_{\text{Rb/Sr}}$ values are <1 , although there is a fairly large uncertainty (± 0.2) in the calculated values.

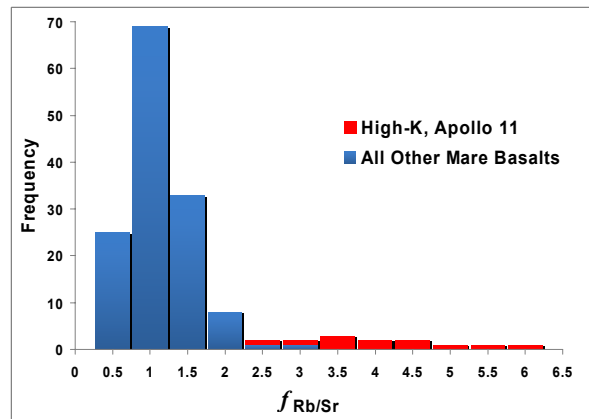


Fig. 1. Histogram showing the Rb/Sr fractionation factor for 147 mare basalts.

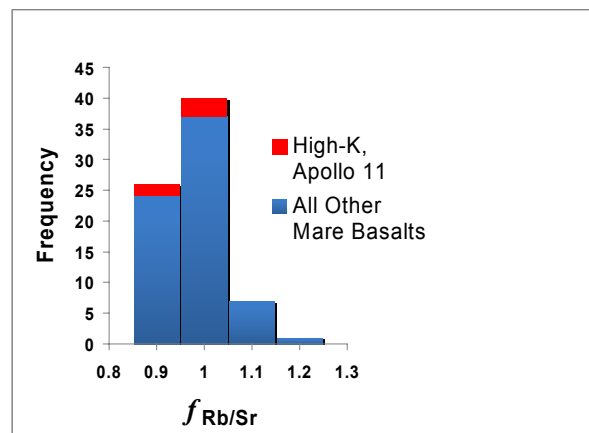


Fig. 2. Histogram showing the Sm/Nd fractionation factor for 76 mare basalts.

Sm/Nd fractionation factors range from ~0.9 to 1.1 (average = 0.93) and all mare basalts lie within a narrow range. Lu/Hf fractionation factors for basalts are 0.44 – 0.49 (15 samples). In addition to the uncertainties in the measured isotopic ratios, the main factor affecting the calculated f values is the present day $^{87}\text{Rb}/^{86}\text{Sr}$ value (and $^{147}\text{Sm}/^{143}\text{Nd}$ and $^{176}\text{Lu}/^{177}\text{Hf}$) since these ratios can be modified by crystal fractionation processes. This effect is likely to be small since the minerals involved in low P fractionation of mare basalt (olivine and pyroxene) will have a minimal effect on

these ratios. In the next section we will examine the roles of variable mineralogy of the source region, near-surface fractionation, and assimilation.

Mantle source regions: Assuming that the calculated fractionation factors were generated at the time of melting of the mantle source it is possible to place constraints on the mineralogy of the source. This is done by solving an equation of the type:

$$F_L = 1 / \{1 + [(1 - f_{Rb/Sr}) / (f_{Rb/Sr} \bar{D}_{Rb} - \bar{D}_{Sr})]\}$$

where F_L is fraction of liquid produced, $f_{Rb/Sr}$ is the fractionation factor, D_{Rb} and D_{Sr} are the bulk distribution coefficients for Rb and Sr, respectively. There are equivalent equations for the Sm-Nd and Lu-Hf systems. D values used in the calculations are given in Table 1. Weight fractions of potential residual minerals are adjusted until F_L becomes equal for all three isotopic systems. However, because there are more unknowns than equations, there is no unique solution.

Table 1. Distribution coefficients used in calculations. Refs: [3], [10], [11], [12], [13], [14].

	plag	cpx	opx	ilm	olivine
Sm	0.033	0.26	0.0085	0.01	0.000445
Nd	0.045	0.174	0.007	0.0073	0.0001
Rb	0.025	0.015	0.009	0.005	0.000044
Sr	2.7	0.116	0.01	0.007	0.000063
Hf	0.013	0.23	0.05	0.4	0.001
Lu	0.015	0.4	0.1	0.09	0.04

Table 2. Several possible solutions that satisfy the mass balance equations for an "average" **high-K mare basalt** ($f_{Rb/Sr} = 4$, $f_{Sm/Nd} = 0.93$ and $f_{Lu/Hf} = 0.45$). Numbers are wt. fractions of residual minerals.

plag	cpx	opx	ilm	oliv	F_L (%)
0.031	0.02	0.001	0.001	0.947	2.6
0.019	0.004	0.4	0.0005	0.5765	1.3
0.0256	0.015	0.05	0.005	0.9044	2.2
0.021	0.01	0.11	0.01	0.849	1.7
0.021	0.01	0.15	0.008	0.811	1.7
0.023	0.009	0.285	0	0.683	1.7

Modeling calculations show that no solutions are possible for $f_{Rb/Sr}$ values less than 1.0. This reflects the choice of D values for Rb and Sr (all residual minerals $D_{Rb} < D_{Sr}$). In all solutions for the high-K Apollo 11 samples, ~2% residual plagioclase is *required* by the high $f_{Rb/Sr}$ values of these samples. All residues are dominated by olivine and orthopyroxene. Maximum residual cpx and ilmenite are 2% and 1%, resp. Extents of partial melting are small. Although residual plagioclase

is required by the high-K samples, high pressure experimental studies carried out on the larger samples indicate that no mare basalts are close to plagioclase saturation at lunar mantle pressures. However, it has been argued [4] that the samples used in the high pressure experiments may not be representative of the average mare compositions, which may be enriched in alumina relative to the hand samples collected.

For all non-high-K mare basalts, residual plagioclase and ilmenite are not required, in agreement with high pressure experimental phase equilibria studies [6]. The three fractionation factors tightly constrain possible solutions to $F_L \sim 2\%$ and a residual assemblage of ~80-84% olivine, ~16-18% opx and ~1-2% cpx.

It can be argued that none of the crystalline mare basalts are primary magmas [4]. However, it is worth noting that low pressure fractionation of liquidus minerals (olivine, pyroxene, ilmenite) has little effect on the calculated fractionation factors, e.g. the Rb/Sr ratio of the magma will not change appreciably. Therefore even if the magmas are evolved, their fractionation factors provide constraints on mantle residua.

Near surface processes: For the high-K A11 suite, our results confirm the conclusions of [2] that the large $f_{Rb/Sr}$ coupled with small $f_{Sm/Nd}$ presents a petrogenetic problem in terms of mantle mineralogy. Near-surface plagioclase fractionation could explain the data but this is unlikely since plagioclase is late-crystallizing (after olivine and pyroxene). Mobilization and redistribution of interstitial melt was suggested by [2] but there is no mechanism to do this on a large scale. As the most plausible petrogenetic model, we suggest that high-K basalts resulted from contamination of primary magmas by KREEP. Addition of a small amount of KREEP can explain the high Rb/Sr, the relatively flat REE pattern and the enhanced negative Eu anomaly.

Conclusions: With the exception of the anomalous high-K basalts, it appears that mare basalts can be produced by low degrees of partial melting (~2%) with a harzburgitic residue. High-K basalts require assimilation of KREEP. Research supported by NASA Grant NNG05GH36G (PI: I.S. McCallum).

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